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INVESTIGATION OF AUDITORY DISCRIMINATION OF SEISMIC SIGNALS FROM EARTHQUAKES AND EXPLOSIONS

Final Report

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Prepared for
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ACOUSTICS AND SEISMICS LABORATORY
Institute of Science and Technology
THE UNIVERSITY OF MICHIGAN

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NOTICES

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PREFACE

The Acoustics and Seismics Laboratory of The University of Michigan's Institute of Science and Technology has conducted research in seismology for several years under the sponsorship of various agencies such as the U. S. Air Force Office of Scientific Research, Air Force Technical Applications Center, Air Force Cambridge Research Laboratories, and National Science Foundation. During the course of this extended program the laboratory has obtained a library of seismic data, which is available for study.

This report investigates an auditory analysis method applied to some of the data, and summarizes 2 1/2 years of study, ending 15 February 1964, sponsored by the Air Force Office of Scientific Research under Contract AF 49(638)-1079 as part of the Advanced Research Projects Agency's VELA UNIFORM program.

Field measurements were obtained primarily under Air Force Contracts AF 49(638)-1170, administered through the Air Force Office of Scientific Research; AF 19(640)-8809 and AF 19(604)-6642, administered through the Air Force Cambridge Research Laboratories; and AF 49(638)-911, administered through the Air Force Technical Applications Center.

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INVESTIGATION OF AUDITORY DISCRIMINATION OF SEISMIC SIGNALS FROM EARTHQUAKES AND EXPLOSIONS

ABSTRACT

Magnetic tape recordings of short-period seismic signals from approximately 200 earthquakes and explosions were time-compressed by a factor of up to 512 to shift seismic frequencies to the audible range. These seismic data include the inhomogeneities introduced by substantial variations in the locations of sources and receivers (world-wide), propagation path length (32 to 7000 km), and source magnitude (M = 0.5 to M = 6.5). Subjects were trained with a representative set of the "seismic sounds." Auditory experiments were conducted to determine the ability of the human auditory system to distinguish between seismic signals from earthquakes and explosions. The results of the experiments suggest that a trained listener can identify approximately two thirds of the seismic sounds presented.

1
INTRODUCTION

Seismological research has been conducted for several years by the Seismics Group at the Acoustics and Seismics Laboratory of The University of Michigan's Institute of Science and Technology. During this extended program the laboratory has accumulated a library of magnetic tape recordings of short-period seismic signals (0.5 to 500 cps) from such sources as earthquakes, nuclear detonations, high-explosive tests, and quarry blasts.

One objective of the research is to investigate techniques which might aid in distinguishing between earthquake seismograms and explosion seismograms. This problem is of primary concern in the VELA UNIFORM program, and has widespread interest within the seismological discipline. Important practical progress has been made by the application of many analytical techniques to seismograms, but it is apparent that new approaches are still needed.

The experiments described in this report were conducted to explore the ability of the human ear to discriminate between earthquakes and explosions by their "audio" signature. Time compression of the tape-recorded signals is used to shift seismic frequencies into the audible range. Should such a subjective technique be found useful, it would represent a rapid means of monitoring seismometer outputs.

After conducting auditory experiments at the Bell Telephone Laboratories, Speeth concluded that listeners identified two classes of events explosions and earthquakes, in over 90%

of the cases presented them [1]. However, experimental data available for that study were severely limited. In later experiments [2] the level of identification was less than 90%, but the results were still not definitive. Thus, though the application of the auditory technique to seismic data is not new, it has not been adequately explored.

The auditory research program reported here proceeded in three phases:

Phase I - Equipment was purchased, built, and integrated to develop an instrumentation system for time-compressing the tape-recorded seismic signals.

Phase II - Seismic recordings were processed through the tape speed-up system, and an auditory data library was built up.

Phase III - The auditory library was used to train subjects and carry out a set of auditory experiments.

2
DISCUSSION AND RESULTS

2.1. SEISMIC DATA

About 200 seismograms of known seismic events were used in this study; examples are shown in Figure 1. They were equally distributed between earthquakes and explosions. Recordings were made in the field with Ampex FM magnetic tape recorders, operated at 3 3/4 ips and using seismic amplifiers built at The University of Michigan (3-db-down points 0.5 and 800 cps). At most stations the field detector was a Hall-Sears (HS-10) 2-cycle geophone, but some of the data were obtained with 1-second Benioff and 1-second Willmore seismometers. Typical field equipment are shown in Figure 2. In a relatively recent innovation, a capacitor across the HS-10 is used to decrease the sensitivity to high-frequency noise. Three earthquake recordings made with short-period instruments were obtained from the Geotechnical Corporation.

The set of field data, then, was obtained with an approximately consistent recording system. Seismometers were generally set up on bedrock and shallow buried to reduce local effects.

Local and near-regional earthquakes were recorded in a number of locations in North America, as well as in Chile, Hawaii, Crete, American Samoa, and Puerto Rico. Also, earthquakes with epicenters in Mexico, the Kurile Islands, Peru, the Azores, and the Aleutians were recorded at teleseismic distances. The propagation distance ranged from 32 to 7000 km. Epicenters were in both water-covered and continental areas. The data cover a range in source magnitude of M = 0.5 to M = 6.5.

The explosions, all recorded in North America, include nuclear detonations, high-explosive tests, underwater shots, and quarry blasts. Source size varied from one-half ton to about 100 kilotons (equivalent in TNT), and the propagation distance varied between 50 and 3100 km.

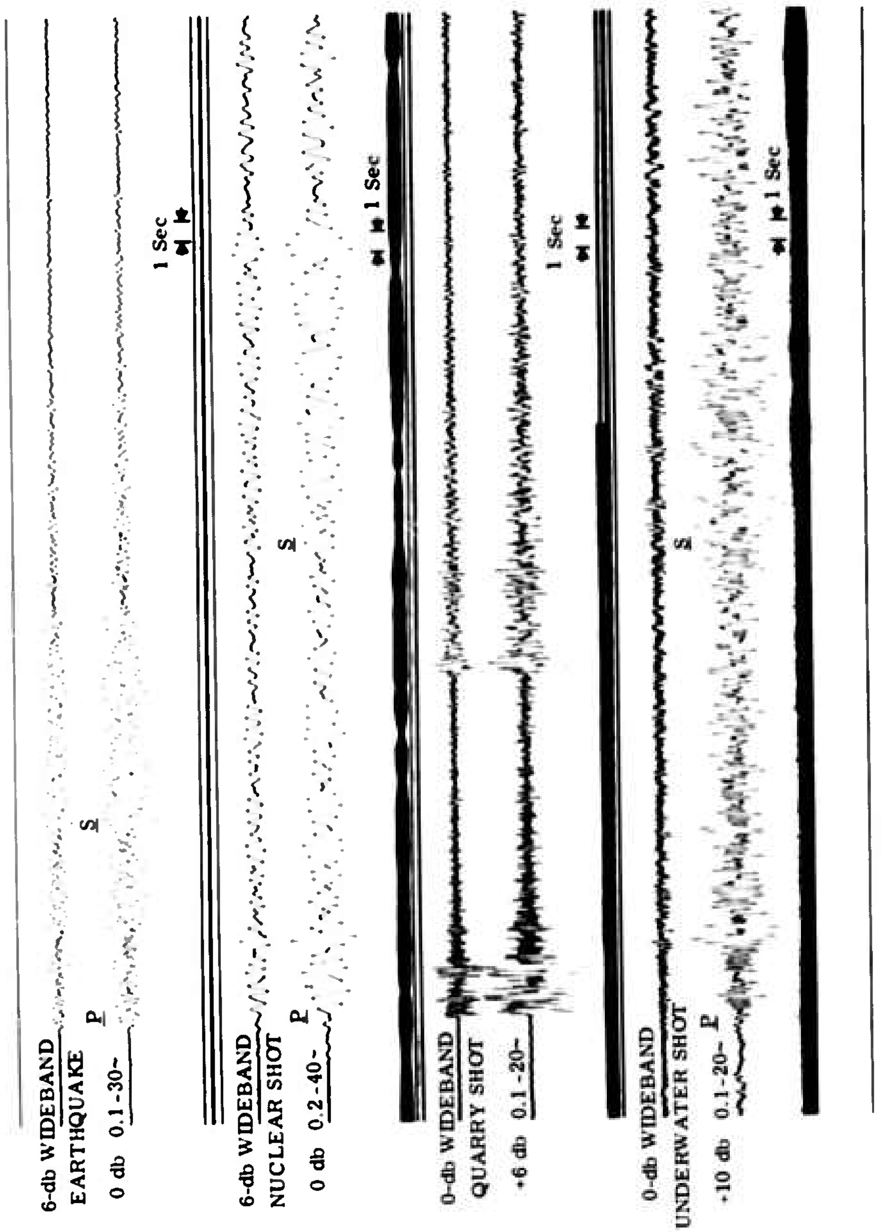

FIGURE 1. EXAMPLES OF SEISMOGRAMS USED IN THIS STUDY. Wideband and passband traces are shown. Playback gain is indicated in db. The seismometer was a two-cycle Hall-Sears.

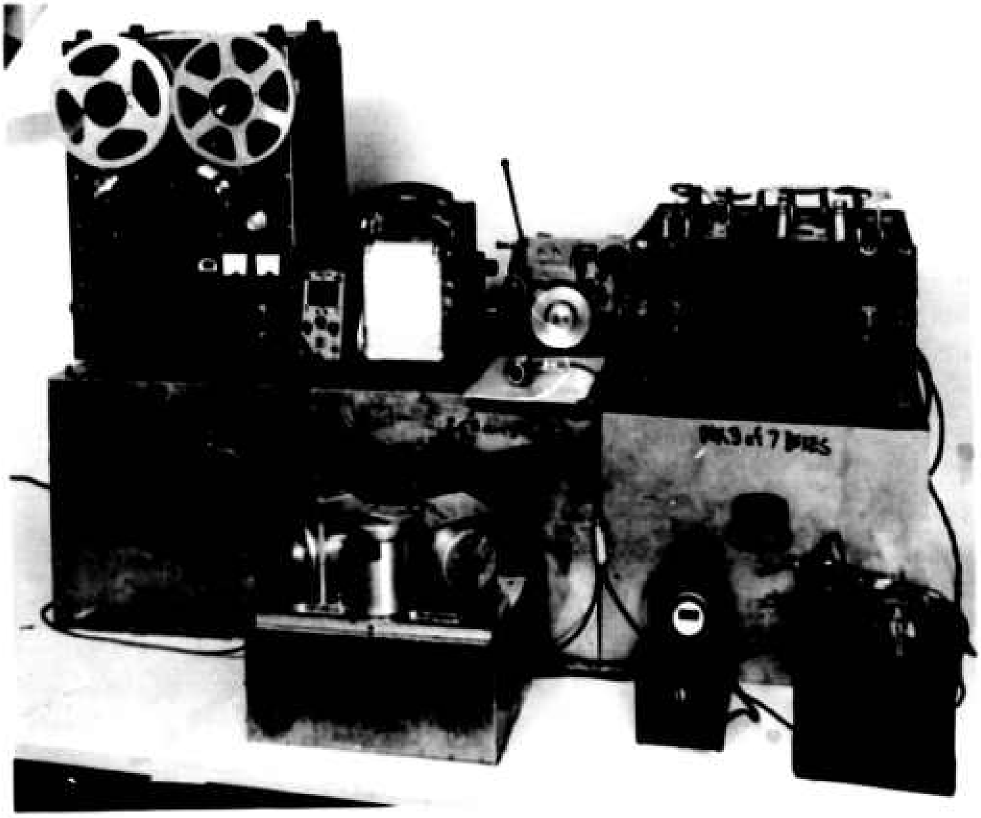

FIGURE 2. TYPICAL FIELD SEISMIC RECORDING EQUIPMENT. Shown, from upper left, are seven-channel FM tape recorder, oscilloscope, level recorder, WWV receiver, seismic amplifiers, three-component HS-10 seismometer, power supply, and batteries.

This data population is such that it is possible to assemble subsets of events with (1) distance held constant and event magnitude varied, (2) distance the variable and magnitude held approximately constant, or (3) complete data inhomogeneity with all parameters varying randomly.

2.2. DATA PROCESSING

The seismic recordings used, which are described in detail in the appendix, are on magnetic tape, a form convenient for time-compressing the data. Figure 3 is a diagram of this speed-up process, and Figure 4 shows the main components of the system. Original field tapes are initially played through a standard data top plate to double the tape speed. The tape is then

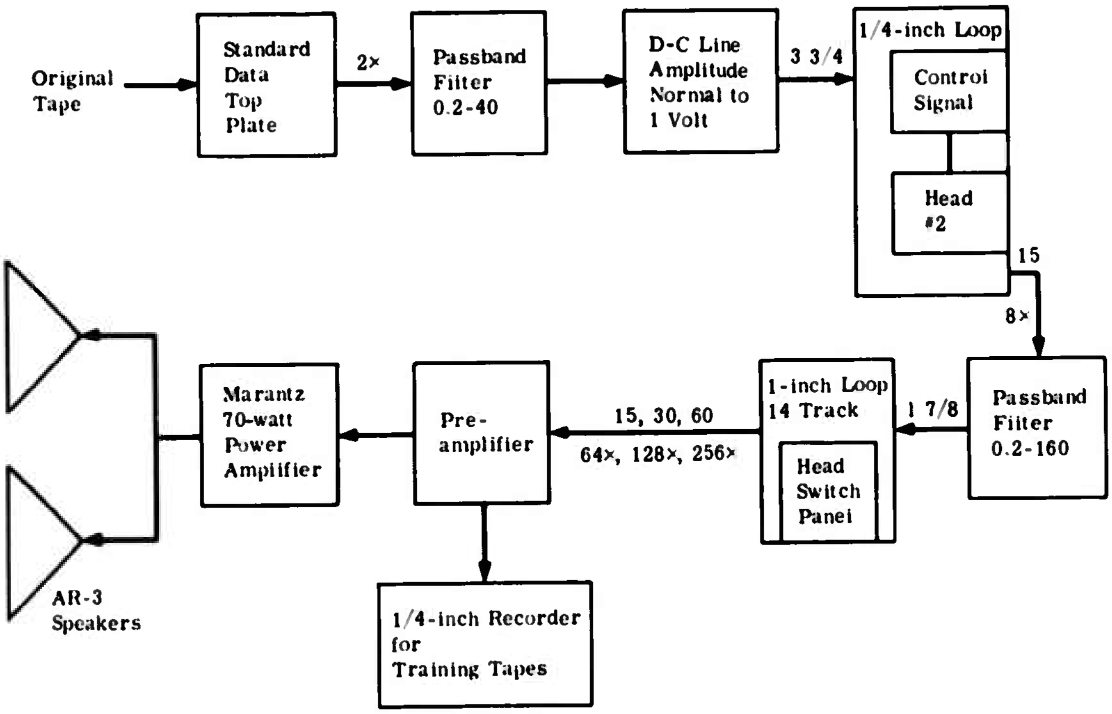

FIGURE 3. TAPE SPEEDUP PROCESS

demodulated and passband filtered at 0.2 to 40 cps (0.1 to 20 cps in real time) to eliminate some of the noise. The next stage consists of a d-c line amplifier which normalizes the data; that is, the maximum amplitude on a seismogram is adjusted to one volt rms. The normalized signals are then recorded at 3 3/4 ips on track one of a 2-track 1/4-inch loop machine (loop length 75 feet) built at The University of Michigan. The second track of the 1/4-inch loop contains a control signal which, at the time the tape splice approaches the reproduce head, switches to a second reproduce head advanced on the loop, thus eliminating the transient otherwise introduced by the splice. Output from the 1/4-inch machine is played at 15 ips, so that at this point in the processing an 8× speedup is achieved. The tape is again filtered, at 0.2 to 160 cps, and then recorded at 1 7/8 ips on one track of a one-inch, 14-track Ampex FL-200 B Loop Machine (loop length 150 feet). The output of this machine is operated at 15, 30, or 60 ips to give over-all time compressions of 64, 128, or 256, respectively. These time compressions can be increased by generating higher speedups in earlier stages of the process—for example, in the 1/4-inch loop machine. The output of the one-inch loop is preamplified, passed through a pair

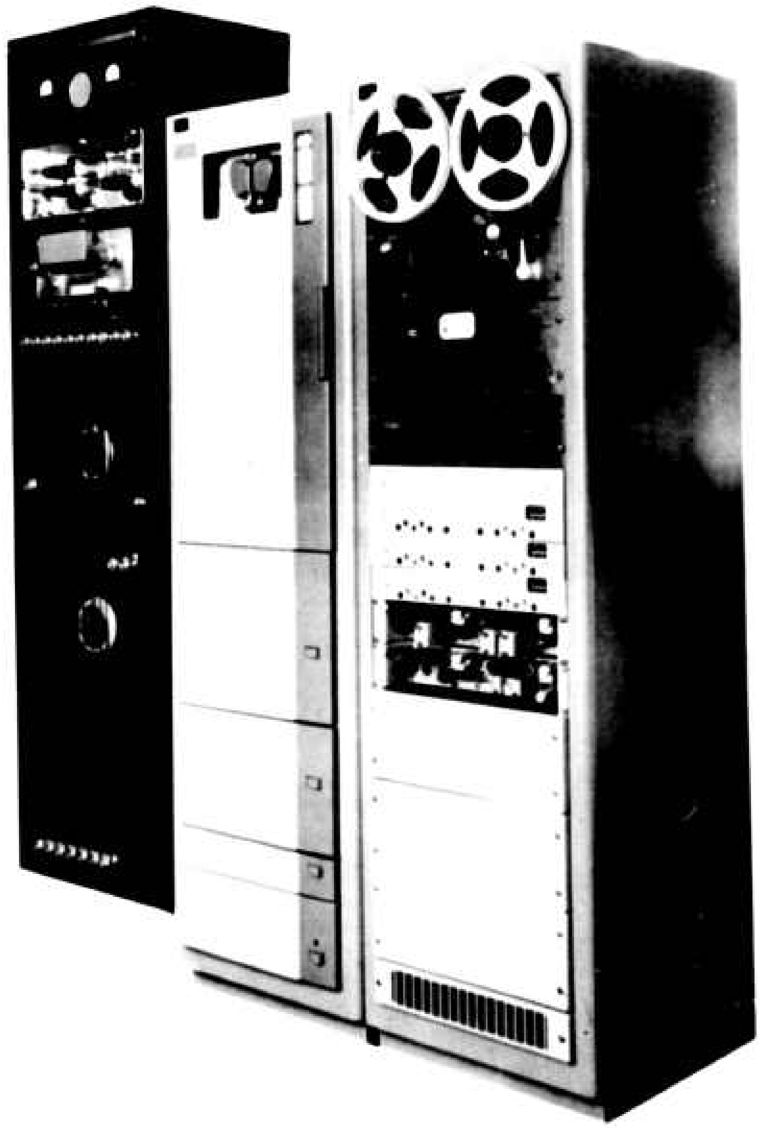

FIGURE 4. PRIMARY COMPONENTS OF THE TIME-COMPRESSION SYSTEM From the left. 1/4-inch loop machine, 1-inch loop machine (door closed), standard data top plate, amplifiers electronics, and power supplies.

of Marantz 70-watt power amplifiers, and finally displayed through a pair of AR-3 speakers in an acoustically favorable room. A second output on the preamplifier stage is recorded on 1/4-inch reels for storage and preparation of training tapes.

The final product of the time-compression process, then, is a set of one-inch, 14-track, 150-foot tape loops. Each loop contains 14 seismic events (one per channel), and each event is repeated 16 times on its channel. A head switching panel associated with the one-inch loop machine enables rapid selection of the desired channel.

2.3. BACKGROUND

The signals recorded on one-inch loops convey complex audio information to the listener. This information consists of multiple stimuli which arise from interrelationships among various phases of seismic waves. Each stimulus must be statistically related to a particular subset of events (earthquakes, EQ, or explosions, EX). Signal identification is then a case of testing statistical hypotheses, where the listener adopts some system of optimizing to select the particular subset a sound belongs to.

For problems in signal detection it has been shown (see, for example, Reference 3) that the best receiver (listener) is the one which calculates a likelihood ratio for each input. In this way the events are mapped onto a single axis. Then the listener can decide which subset an input was taken from by applying some rule pertaining to likelihood, or to some point on the axis. If there are many stimuli associated with a given input, as in the seismic case, it is necessary to calculate a separate likelihood ratio for each criterion. The possibility of there being as many criteria as there are listeners is perhaps not remote.

Since, in fact, it is not possible to identify all the stimuli, it is difficult to conduct experiments based on an optimizing procedure which comprehensively investigate the auditory discrimination capability in the seismic case. However, we anticipate that the combined effect of multiple criteria can be readily explored by evaluating the behavior of listeners in a "sound identification" program according to the percentage of correct decisions.

Tanner [4] expands the theory of auditory detection of signals to treat a simple signal recognition problem, with the support of auditory experiments. His argument will not be reproduced here, but it does demonstrate that the theory of statistical decision is applicable to the problem of recognition.

The available data in this study, then, consist of two subsets: population EQ (earthquakes) and population EX (explosions). A sample is drawn from one of these two distributions, and the observer must identify the distribution from which it was taken. We define a decision region, A, such that if an observation falls in this region the listener accepts the hypothesis that the event is in the set EQ. If the observation falls in the region CA, the listener accepts the hypothesis that the event is in the set EX. Thus we have for the possible outcomes of the experiment

$$P(EQ \cdot A) + P(EQ \cdot CA) + P(EX \cdot A) + P(EX \cdot CA) = 1 \tag{1}$$

where the terms on the left, in order, are the probabilities that (a) given EQ the listener will accept it as EQ, (b) given EQ he will accept it as EX, (c) given EX he will accept it as EQ, and (d) given EX he will accept it as EX. Now the conditional probabilities associated with the experiment are such that the following statements may also be made:

$$P(EQ) + P(EX) = 1 \tag{2}$$

$$P(EQ) = P(EX) = 0.5 \tag{3}$$

$$P_{EQ}(A) + P_{EQ}(CA) = 1 \tag{4}$$

$$P_{EX}(A) + P_{EX}(CA) = 1 \tag{5}$$

Since Equations 4 and 5 equate to one, we may describe the performance of listeners with just two probabilities, for example $P_{EQ}(A)$ and $P_{EX}(A)$. The former is the probability that a listener will identify an EQ correctly. The latter is the probability that he will identify an EX as an EQ. In the literature these are referred to as <u>hit rate</u> and <u>false alarm rate</u>, respectively, and by standard definition in formal probability theory they are

$$\begin{aligned} P_{EQ}(A) &= \int_A f_{EQ}(x)\,dx \\ P_{EX}(A) &= \int_A f_{EX}(x)\,dx \end{aligned} \tag{6}$$

where the integration is over all points in region A, and the integrands are the probability density functions of sample variable x for the cases when x is drawn from populations EQ and EX, respectively.

In terms of the density functions above, likelihood ratio can be expressed as

$$f(x) = \frac{f_{EQ}(x)}{f_{EX}(x)} \tag{7}$$

Suppose we ask the listener to maximize his hit rate relative to his false alarm rate; that is,

$$P_{EQ}(A) - \omega\, P_{EX}(A) = \max \tag{8}$$

which is the same as maximizing the integral

$$\int_A [f_{EQ}(x) - \omega f_{EX}(x)]\, dx = \max \tag{9}$$

Then we see that the decision rule involves a ratio criterion. Specifically this says choose region A such that

$$f(x) \geq \omega \tag{10}$$

ω being the weighting factor introduced in Equation 8.

Consider the probability density functions in the seismic recognition problem to be as shown in Figure 5. The extent to which seismic signals can be discriminated is depicted by the separation of the means of distributions EX and EQ. If the listener chooses a criterion cut at some point C (related to a specific value of likelihood ratio), then the cross-hatched area is a measure of hit rate and the stippled area is a measure of false alarm rate. As the cut is moved to different positions on the decision axis, the conditional probabilities change and a set of points relating hit rate and false alarm rate is generated. The relationship between such points is known as an ROC (receiver operating characteristic) curve. If these points plot in a straight line with slope one when presented on double-probability paper, the probability densities are normally distributed and have equal variance.

The value of an ROC presentation is that it completely describes an observer's performance in "sensory" experiments where decisions are based on ratio criteria. Because of the inherent

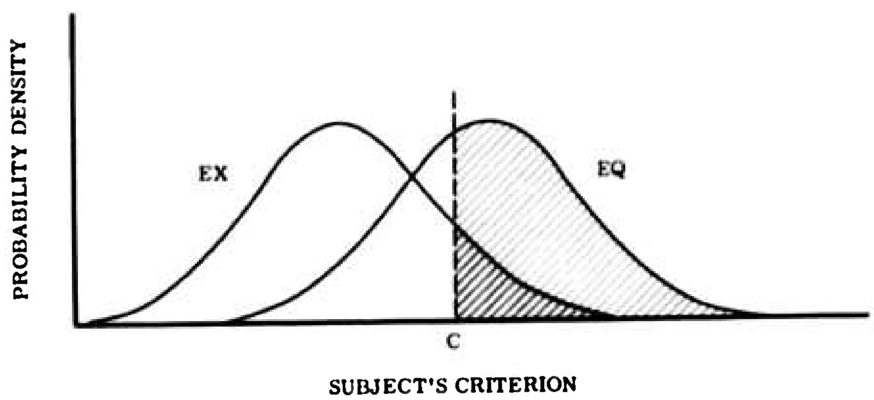

FIGURE 5. HYPOTHETICAL PROBABILITY DENSITY FUNCTIONS OF EQ AND EX AS A FUNCTION OF LISTENER CRITERION. An arbitrary cut C related to likelihood ratio is shown. The cross-hatched area represents $P_{EQ}(A)$, and the stippled area represents $P_{EX}(A)$.

complexity of seismic signals, we choose to measure the auditory performance on the basis of percentage of correct decisions, always with the underlying objective of obtaining, if possible, likelihood ratio information of the type described. The experiments are described in the following section.

2.4. EXPERIMENTAL PROCEDURE

The auditory program consisted of two experiments, Series A and Series B. Series A was carried out at the time when approximately 125 seismic events were time-compressed. This series, which lasted two months included training sessions and eight test sessions. It was conducted (1) to obtain an early indication of results (after preliminary training); (2) to investigate such factors as auditory stimuli, speedup, filtering, and listening to tapes played backwards; and (3) to increase the listener's skill. Series B was carried out after the entire sample (about 200 events) was time-compressed. This series, which also lasted two months, included training sessions and 16 test sessions. It was conducted (1) to obtain definitive results of the percentage of correct decisions that a trained listener could achieve in an identification program of random, inhomogeneous seismic sounds; (2) to generate data, if possible, to describe the observer's performance by an ROC curve; and (3) to compare auditory results with analytical results obtained with the same raw data. Listeners were trained both before and during both series of experiments. For this purpose data other than the test data were used.

In all experiments the subjects (from 9 to 13 per session) were seated in an acoustically favorable room in which two AR-3 speakers were located. All other related equipment remained in a separate room. Each event played through the speakers was preceded and followed by a short segment of background noise which conditioned the ear to the impending signals. Each test sound was presented four times, the listeners having decided that four was optimum. Although the a priori probability of a given event's being an EQ or EX was 0.5, the order of presentation of unknown sounds was random (based on random number tables). In the various test sessions, data were grouped to give the following combinations of parameters: (1) distance the constant and event magnitude a variable, (2) distance the variable and event magnitude approximately constant, and (3) complete data inhomogeneity with all parameters varying.

2.4.1. SERIES A. Series A was a simple two-choice experiment in which listeners responded either EQ or EX. A total of 21 observers took part in this experiment, although no more than 13 were present in any given test session. Subjects for both series were staff members of the Acoustics and Seismics Laboratory, including engineers, technicians, secretaries, and student assistants.

Early phases of this experiment investigated the effect of filtering. Seismograms were exposed to different passband filters, and results were assessed in the listening program. For most of the recordings, a decrease in the high-frequency cutoff to 10 cps did not result in any perceptual change in the audio output. High-frequency seismograms from local earthquakes recorded in Chile, and certain other recordings of near events (< 150 km), were the main exceptions. In fact, a high-frequency limit of 5 cps appeared to be satisfactory for most sounds obtained at distances exceeding about 300 km. The low-frequency cutoff could not be raised above 0.5 cps without introducing noticeable loss of information in the output. The system response for data gathered for this study decreases rapidly below 0.5 cps. We infer from these observations that the critical frequency window for a majority of real-time seismic data is approximately 0.5 to 5 cps. To allow a margin of safety in this study we chose to filter the original seismograms at 0.1 to 20 cps, which is limited enough to exclude much of the spurious noise. In exceptional cases the high-frequency cutoff was appropriately increased above 20 cps to include all short-period seismic energy.

A trial and test procedure similar to that described above was conducted to explore the effect of different time-compression factors, which ranged from one (real time) to 512. On the basis of listeners' performance, it was determined that a time-compression factor of 128 is optimum for events recorded in the approximate range from 200 to 1000 km. This result suggests that in the speed-up process a minimum of about 1/4 second should be maintained between the predominant P and predominant shear-surface arrivals, and that the overall signal duration should be less than about 2 seconds.

A résumé of results for eight test sessions in Series A is shown in Table I. P(c) is the mean percentage of correct identifications for the group of listeners present at each test session, and σ is the standard deviation of the mean. The values of P(c) for tape loops number 4 and 11 in this table are examples of the type of evidence which supports the time-compression vs. distance relationship. Seismic events on those loops are in the ranges 214 to 284 km and 270 to 780 km, respectively, for which the factor 128 is optimum.

Three of the data loops were run backward in some tests, with the idea that the late-arriving coda of waves on a seismogram might be a preferred "first arrival" to the ear over the much more abrupt first P arrival. The results for backward listening, tabulated with a symbol (B) in the P(c) column of Table I, indicate that backward listening does not improve discrimination. However, it turns out that subjects become confused when forced to listen to seismograms in both directions. For example, one of the decision criteria is "attack time," which is longer for earthquakes in the forward direction but longer for explosions in the opposite direction. Thus, to properly exploit reversed playing of seismic sounds, one should train a separate group of subjects.

TABLE I. RESULTS FOR SERIES A

Session	Loop	No. of Observers	Responses	Speedup	P(c)	σ
1	5	9	504	128X	0.57	0.08
2	4	12	864	64X	0.60	0.08
				128X	0.68	0.07
				256X	0.59	0.08
3	8	13	910	128X	0.58	0.08
4	10	13	910	128X	0.65	0.14
5	10	11	770	128X	0.62(B)	0.08
6	6	10	400	64X	0.58	0.10
				64X	0.55(B)	0.10
	7	11	400	64X	0.63	0.07
				64X	0.61(B)	0.08
7	9	11	528	64X	0.82	0.09
	11	11	528	128X	0.60	0.12
8	11	12	432	256X	0.51	0.06

From the data in Table I, the mean P(c) for Series A is

$$\overline{P}(c) = 0.64 \pm 0.07 \tag{11}$$

This average is based on all data exclusive of (a) results for non-optimum speedups in the case of loops 4 and 11 and (b) scores labeled (B).

2.4.2. SERIES B. Series B was a forced-choice experiment in which listeners responded in one of four categories and attempted to maximize the value of their response. The response categories and their ratings are given in Table II. It is considered that if an observer is required to make a discrete response, as in Series A, then some information available to him is discarded in the decision process. In using a rating system, the listener is, in a sense, making a statement of likelihood, and thus more of the auditory information is retained in his response. This rating system was chosen for its simplicity.

TABLE II. VALUES AND COSTS ASSOCIATED WITH FOUR RESPONSE CATEGORIES

Response	Rating: Correct Decision	Rating: Incorrect Decision
I'm sure it is EQ	+2	-2
I think it is EQ	+1	-1
I think it is EX	+1	-1
I'm sure it is EX	+2	-2

A total of 19 observers took part in the Series B experiment. No more than 12 were present in any given session, and 12 of the 19 also took part in Series A.

Table III outlines 11 sessions, in which 16 data loops were tested. In this table P'(c) refers to the weighted average of the group percentage of correct identifications for each data loop. In Table III the results of all 19 subjects were used. Decisions in the rating category +2 were given a weighting of 1, and decisions in the rating category +1 were given a weighting of 0.75. The mean of these group averages is

$$\overline{P}'(c) = 0.648 \pm 0.054 \tag{12}$$

Comparison of Equations 11 and 12 indicates that indeed there is no significant difference between the results for Series A and Series B.

TABLE III. RESULTS FOR SERIES B

Session	Loop	Number of Observers	Responses	Speedup	P'(c)
1	9	8	336	64×	0.651
2	7	12	504	64×	0.635
3	6	10	420	64×	0.649
4	8	11	462	64×	0.672
5	4	10	420	128×	0.663
6	12	10	420	64×	0.692
	10	10	420	128×	0.764
7	13	12	504	128×	0.659
	13	12	504	128×	0.705
8	14	9	378	128×	0.652
	11	8	336	128×	0.546
9	15	10	420	128×	0.614
10	16	9	378	256×	0.699
	5	9	378	128×	0.587
11	14	12	504	128×	0.665
	11	12	504	128×	0.566

We then computed the mean P'(c) for each individual subject (on the basis of his entire Series B performance). The results are listed in Table IV and plotted in the bar graph of Figure 6. From these data we note that subjects' performance ranges from 0.516 to 0.744. In analyzing this variation we first designated, by x at the top of Figure 6, those listeners who attended nine or more of the 16 data-loop tests in Series B. The unmarked subjects attended only one to four of the tests. We suggest that the results of the eight listeners in the latter category should be neglected because of insufficient sampling.

The listeners were instructed to listen for certain auditory stimuli and judge them on the basis of specified criteria; that is, they were to use a weighted-criteria decision technique. Subjects 14M and 17M did not use such a system, and we have evidence that subject 11F (who attended the minimum of 9 tests) also failed to apply this technique. On this basis we recomputed the mean P'(c) for group averages of Table III, using only the results of listeners 1 through 8, getting

$$\bar{P}'(c) = 0.677 \pm 0.057 \tag{13}$$

Results for Series A and Series B can now be compared on the basis of Equations 11 and 13.

TABLE IV. MEAN P'(c) FOR EACH SUBJECT—SERIES B

Subject	$\bar{P}'(c)$	Subject	$\bar{P}'(c)$	Subject	$\bar{P}'(c)$
1M	0.744 ±0.115	8M	0.633 ±0.091	15M	0.590 ±0.030
2F	0.709 ±0.089	9M	0.629 ±0.046	16M	0.580 ±0.000
3F	0.701 ±0.117	10M	0.627 ±0.079	17M	0.567 ±0.082
4M	0.681 ±0.092	11F	0.622 ±0.087	18F	0.542 ±0.132
5M	0.656 ±0.080	12M	0.622 ±0.055	19M	0.516 ±0.027
6F	0.648 ±0.071	13F	0.616 ±0.189		

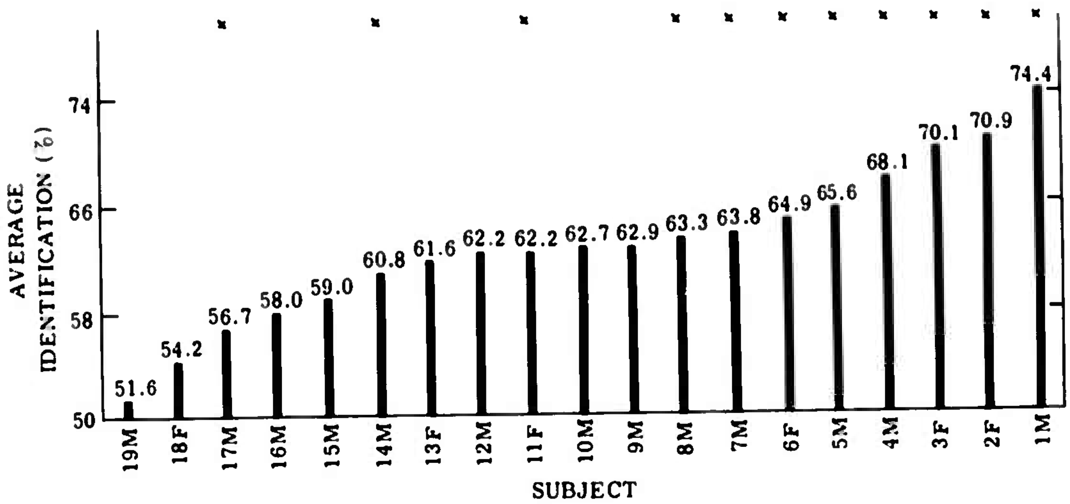

FIGURE 6. $\bar{P}'(c)$ FOR 19 SUBJECTS IN SERIES B TESTS. The letters M and F denote male and female subjects. The x at the top identify those subjects who attended nine or more of the 16 series B tests.

2.5. DISCUSSION

So far we have evaluated the auditory performance by the percentage of correct identifications, using an unweighted mean $\overline{P}(c)$ of all subjects in Series A and a weighted mean $\overline{P}'(c)$ of eight selected subjects in Series B. We can analyze the data for additional information by examining the rating responses of Series B in greater detail. Though it is difficult to establish likelihood ratio data for each of many complex stimuli, we can break down the net effect into strict (+2, -2) and lax (+1, -1) criteria. This has the effect of translating a cut along the decision axis, as indicated in Figure 5, and should generate operating characteristic data of the type discussed earlier. A table was made up for each of the 19 listeners to summarize total responses in each of the categories +2, +1, -1, -2 for both subsets, EQ and EX. From these entries individual probabilities and cumulative probabilities were determined. The results of this statistical calculation are shown in Figure 7, in which $P_{EQ}(A)$ is plotted on the ordinate and $P_{EX}(A)$ on the abscissa of double-probability paper. The positive diagonal of these normal-normal graphs is the chance line. For clarity, lines are not drawn through individual points, but in general the data for listeners 1 through 8 do approximate a linear relationship with unity slope. (These parameters must be referenced to the deviate scale to the right and top of the graph.) However, the points for subjects 9 through 13 become erratic, and those for subjects 14 through 19 approach the chance line. We are reminded about statements made earlier concerning listeners 9 through 19: that eight of them had an inadequate auditory sample and at least two of the other three did not use a weighted-criteria decision technique.

A negative semi-diagonal is drawn on the graphs of Figure 7. One of the significances of this is that the intersection of a straight line (through any set of points) with this diagonal scales equal probabilities for identification of earthquakes and explosions. Points for the best subjects were connected; the resulting ROC curve is plotted on linear coordinates in Figure 8. Observe from this curve that at the point of maximum difference between hit rate and false alarm rate the percentage of correct identification is about 67.5% (equal for EQ and EX).

2.6. RESULTS

In the interpretation of these data the question whether the experiment was adequate naturally arises. We exposed each subject to an average of 1500 auditory decisions in the combined training and testing program. Is this sufficient? It is possible that the rating method automates the learning process so that the listener reaches a plateau in performance more rapidly than by the two-choice procedure alone. A set of data bearing on this aspect of the experiment is presented in Figure 9, a plot of the results throughout the Series B tests for 11 listeners. The points are relative to an arbitrary mean, and the dashed lines are least-square lines which show how each subject's performance varied with time (time and experiment are synonymous here).

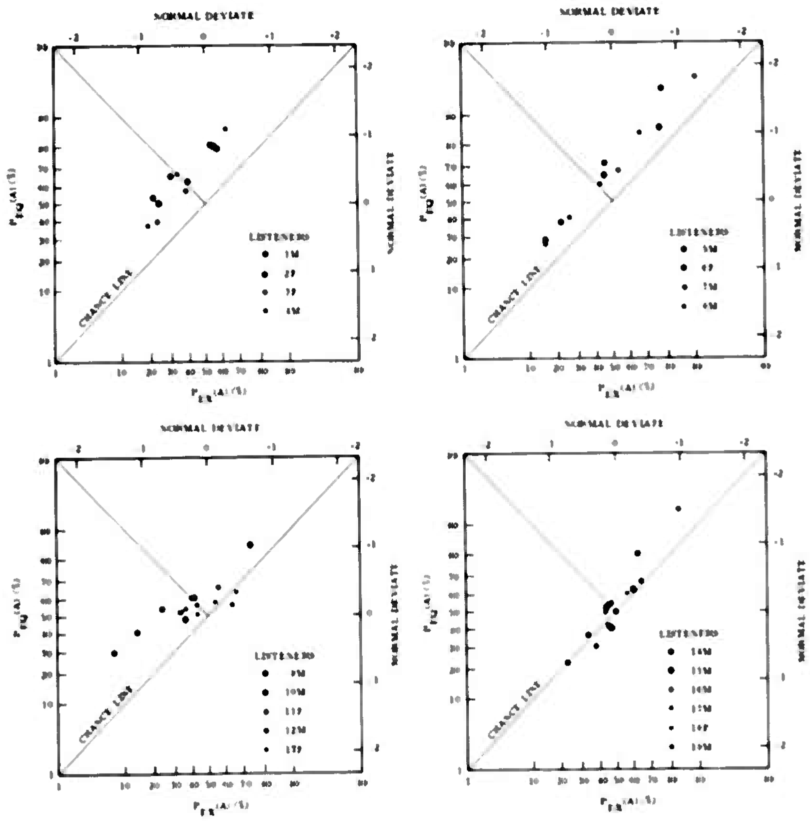

FIGURE 7. PLOT OF $P_{EQ}(A)$ VS. $P_{EX}(A)$ FOR 19 SUBJECTS. $P_{EQ}(A)$ is plotted against $P_{EX}(A)$ on double-probability paper. The slope of the best-fit straight line to individual sets of points is determined from the deviate scales.

A positive slope, such as that for observer 4M, indicates that the listener was still improving at the end of the experiment. A negative slope, such as that for observer 3F, means the opposite. We note that the results for most of the subjects are flat (in the least-squares sense).

Another question concerns the rather wide variation between performance of individuals. Part of this difference is obviously due to the inadequate sampling of some subjects. We obtained Maico audiograms of 13 listeners, looking for possible correlations of auditory results with frequency variations in individual hearing levels. These data are shown in Figure 10. Most of the audiograms are near "normal." One of the better subjects, 4M, has a hearing loss of about 40 db per octave above 1000 cps. No correlation is evident.

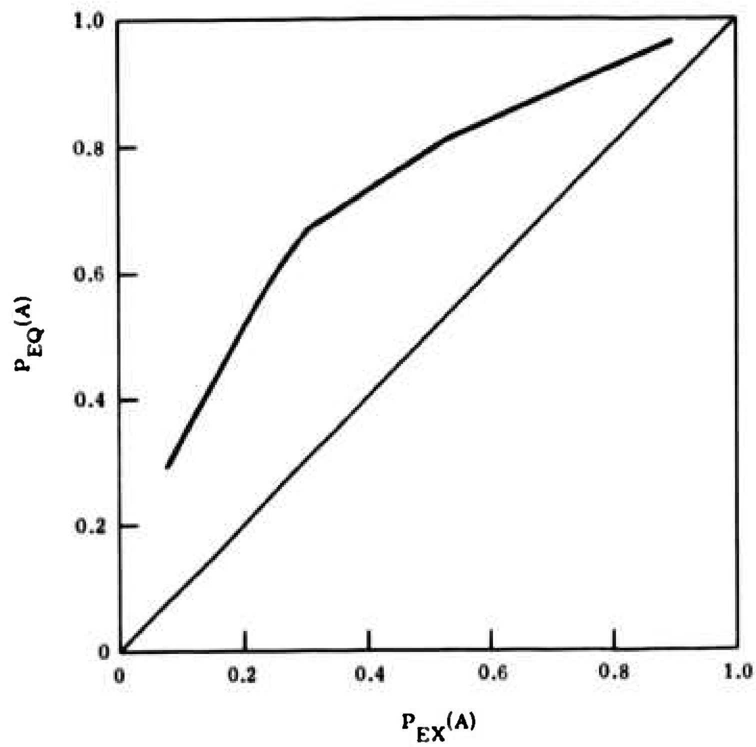

FIGURE 8. ROC CURVE FOR THE BEST SUBJECTS. The positive diagonal is the chance line. The slope of the curve at a particular operating point is related to the weighting factor ω introduced in Equation 8.

An interesting observation which can be given only cursory examination in this report is shown in the data of Table V. Most of the seismograms used in the study were vertical-component ones, but this table contains exceptional cases where horizontal components were also time-compressed. Column P(c) contains listening results for the cases when the channels were analyzed separately. Column $P_D(c)$ contains the results of dual-component listening where a vertical component and a horizontal component were simultaneously played through separate speakers. In the few cases tested, auditory recognition is improved by the addition of the second dimension.

Finally, it would be significant to compare the auditory analysis method to an analytical technique, both applied to the same seismic data. Many of the seismograms used in this report were studied by others [5, 6], who investigated the discrimination of seismic signals on the

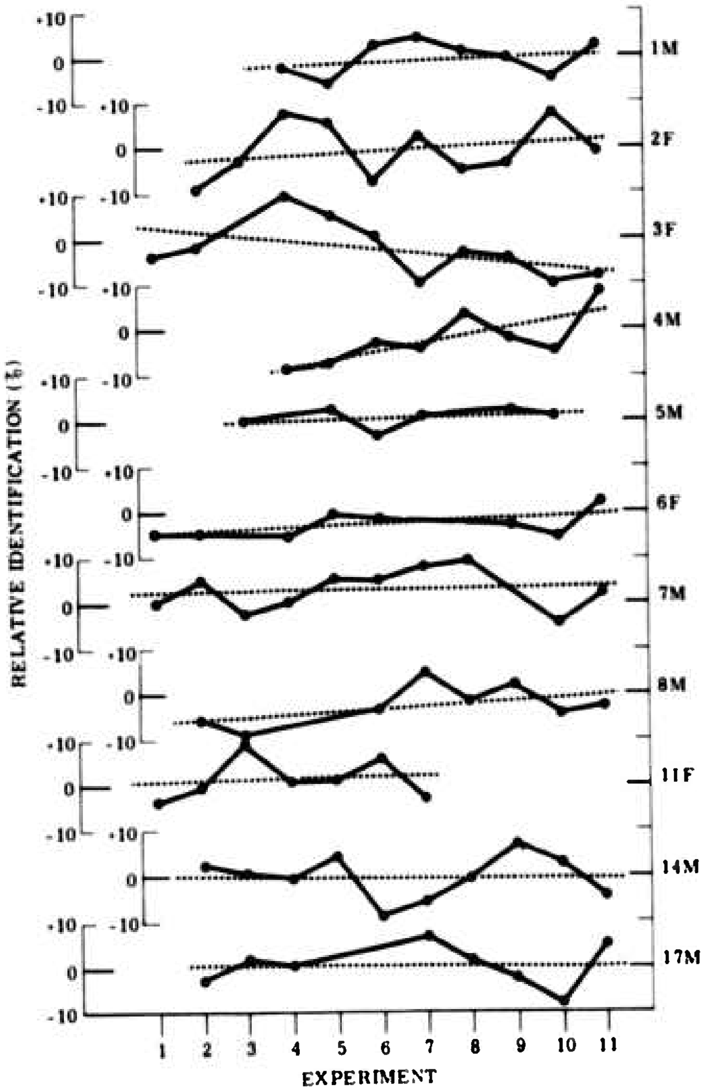

FIGURE 9. CHRONOLOGICAL RESULTS FOR 11 SUBJECTS IN SERIES B TESTS. Points are referenced to a relative mean, and least-square lines (dashed) show the variation in performance with experiment or with time. A positive slope indicates that subjects are still improving at the end of the experiment. A negative slope means the opposite.

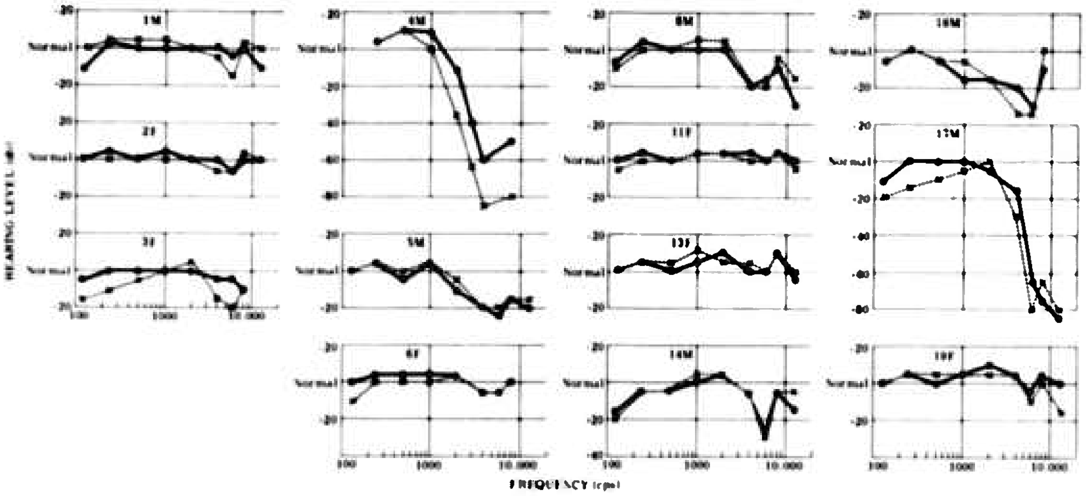

FIGURE 10. MAICO AUDIOGRAMS FOR 13 SUBJECTS. Solid and dashed lines are for right and left ears, respectively.

TABLE V. DUAL-COMPONENT VS. SINGLE-COMPONENT LISTENING

Recording	Event	Distance (km)	M	Component	P(c)	$P_D(c)$
Castle Cliffs, Utah	N-Coll.	217	3.0	Z	0.907	0.960
Castle Cliffs, Utah	N-Coll.	217	3.0	T	0.945	
Ramona, Calif.	EX-Q	150		Z	0.146	0.194
Ramona, Calif.	EX-Q	150		R	0.228	
Luera Ranch, N. Mex.	EQ	315	2.2	Z	0.669	0.842
Luera Ranch, N. Mex.	EQ	315	2.2	T	0.633	
Luera Ranch, N. Mex.	EQ	315	2.2	Z	0.665	0.749
Luera Ranch, N. Mex.	EQ	315	2.2	R	0.523	
Quarter Master V. P., Ariz.	EX-N	235	2.6	Z	0.528	0.627
Quarter Master V. P., Ariz.	EX-N	235	2.6	T	0.484	

basis of the ratio of compressional wave amplitude to shear-surface wave amplitude. One way of comparing results would be by likelihood ratios. In Table VI we illustrate a technique for calculating likelihood ratio data from other criteria by using probabilities. The first column lists the different stimuli or divisions of a criterion. The second and third columns give the number of times each stimulus is observed for EQ and EX. These columns are summed and the individual probabilities determined as indicated in the fourth and fifth columns. Likelihood ratio

TABLE VI. LIKELIHOOD RATIO CALCULATION

Criterion	EQ	EX	$P_{EQ}(x)$	$P_{EX}(x)$	f(x)
1	n_1	m_1	$n_1/\Sigma n_i$	$m_1/\Sigma m_i$	$n_1/\Sigma n_i \div m_1/\Sigma m_i$
2	n_2	m_2	$n_2/\Sigma n_i$	$m_2/\Sigma m_i$	$n_2/\Sigma n_i \div m_2/\Sigma m_i$
3	n_3	m_3	$n_3/\Sigma n_i$	$m_3/\Sigma m_i$	$n_3/\Sigma n_i \div m_3/\Sigma m_i$
4	n_4	m_4	$n_4/\Sigma n_i$	$m_4/\Sigma m_i$	$n_4/\Sigma n_i \div m_4/\Sigma m_i$
	Σn_i	Σm_i			

f (x) is then the ratio of the corresponding probabilities. Table VII presents the results of carrying out this calculation on seismograms used in this report. In addition to the amplitude ratio mentioned above, we have also established the values of f(x) for event magnitude and range. These are readily compared with the auditory data in the table. The significance of f(x) is indicated by the extent to which it deviates from unity (either + or -).

One objective of the auditory experiments was to test the listeners' performance as a function of seismic propagation distance. In Table VIII we present these results. Note that there indeed is some variation in $\overline{P}'(c)$ with distance, although it must be admitted that 65% of the seismic data available in this study were in the epicentral distance range from 100 to 400 km. It is interesting to note also (in Table VIII) the percentages (p^*) obtained by Willis, et al. [5], from the same seismic data; p^* is the percent of earthquakes which have a shear/compressional wave amplitude ratio greater than the corresponding ratio for nuclear explosions. The last result in the $\overline{P}'(c)$ column of Table VIII was obtained in auditory experiments when distance was allowed to vary randomly over a broad range (100 to 3000 km) in a given listening test and time compression was held <u>constant</u>. The reader is reminded that the p^* column depicts EQ identification, whereas the $\overline{P}'(c)$ column depicts approximately equal identification of EQ and EX.

TABLE VII. COMPARISON OF ANALYSIS TECHNIQUES

Auidtory	f(x)	S/P Max.	f(x)	M	f(x)	R(km)	f(x)
+2	2.04	<0.63	2.24	<1	.48	<100	1.46
+1	1.34	0.63-1.25	0.77	1-2	1.54	100-200	1.11
-1	0.75	1.25-2.5	0.64	2-3	0.97	200-400	0.58
-2	0.49	2.5-3.75	2.08	3-4	0.69	400-1000	1.29
		3.75-5.0	0.77	4-5	1.59	1000-3000	0.61
		5.0-10.0	3.16	5-6	1.07	3000-7000	2.97

TABLE VIII. DISCRIMINATION PERCENTAGE AS A FUNCTION OF EPICENTRAL DISTANCE

$\overline{P}'(c)$ (%)	Epicentral Distance (km)		p^* (%)
71	35-100	50-100	85
68	100-200	100-200	59
71	200-400	200-400	52
59	400-700	400-1000	67
63	700-1700		
70	3000-7000		
60	100-3000		

*From Reference 5.

3 CONCLUSIONS

Seismic signals from approximately 200 sources (earthquakes and explosions) were time-compressed, and an experimental training and testing program was conducted with the resulting audio sounds. Experimental parameters were controlled to cover various combinations of seismic variables, but the inhomogeneity characteristic of typical field seismograms was preserved and the signals were presented to the listeners in random order.

There are several ways of analyzing this kind of data. In selecting an approach, we were guided in part by the multiplicity and complexity of auditory stimuli associated with seismograms. One method measured the observer's performance on the basis of percentage of correct identifications. On this basis, the mean score for all listeners is about 65%, and the weighted score for the eight subjects who most closely adhered to the experimental demands is about 68%.

An alternative technique classified the observer's responses in a simple four-category rating system which, basically, partitioned the decisions according to "strict" and "lax" criteria. On this basis, the optimum listener identified about 67.5% of the earthquakes and explosions. This result is based on a priori probabilities of EQ and EX being 0.5. The added significance of the alternative technique is that an ROC curve was generated. Techniques are available in the literature (e.g., References 7 and 8) which make it possible, by using ROC data, to translate the result stated above into a domain where other a priori probabilities exist.

In this experiment each subject was required to make approximately 1500 auditory decisions. One might speculate on the significance of a much more intense auditory program. Our data do indicate that most of the listeners apparently reached a plateau in mean performance.

We conclude, then, that the optimum trained observer using a subjective technique of auditory analysis identified approximately two thirds of the seismic signals consisting of a random, inhomogeneous set of 200 earthquake and explosion seismograms. Each of these events was recorded at one geographic location. If multiple statistically independent recordings of the same event are available (say from a global distribution of seismic stations) then in theory the curve of Figure 8 can be raised 3 db for each twofold increase in the number of stations.

In a practical application of the auditory technique, if the inhomogeneity of seismic data were limited by using recordings from only <u>one</u> station, then it is conceivable that the result of this experiment could be improved. This is particularly expected if discrete "unknown" signals are tested by comparison with known reference signals, both EQ and EX, peculiar to the azimuth and range estimated for the "unknown" ones.

Appendix
DESCRIPTIONS OF SPEEDED-UP DATA LOOPS USED IN THE TESTS

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
TAPE LOOP NO. 4							
1	EQ	7/28/60	Kingman, Ariz.		276	VB	3.1
2	N-EX		Kingman, Ariz.	NTS, Nev.	265	VHS	3.4
3	EQ	8/24/59	Shepherd, Mont.	Hebgen Lake, Mont.	250	VW	1.8
4	N-EX		Kingman, Ariz.	NTS, Nev.	265	VHS	2.2
5	C-EX	10/13/60	Fletcher, Nev.	NTS, Nev.	265	VW	3.8
6	N-EX		Quarter Master View Pt., Ariz.	NTS, Nev.	235	VW	2.6
7	EQ	8/24/59	Shepherd, Mont.	Hebgen Lake, Mont.	235	VW	2.0
8	N-EX		Climax Claims, Ariz.	NTS, Nev.	226	VW	4.8
9	Q-EX	7/13/62	Fiborn Quarry, Mich.	Humboldt, Mich.	214	VHS	2.7
10	N-EX		Climax Claims, Ariz.	NTS, Nev.	220	VW	2.2
11	C-EX	10/13/60	St. George, Utah	NTS, Nev.	220	TB	3.4
12	N-EX		Climax Claims, Ariz.	NTS, Nev.	215	VW	2.8
13	C-EX	10/13/60	St. George, Utah	NTS, Nev.	220	LB	3.7
14	N-EX		Climax Claims, Ariz.	NTS, Nev.	220	TW	2.8

EQ—Earthquake
N-EX—Nuclear explosion
C-EX—Chemical explosion
Q-EX—Quarry explosion
U-EX—Underwater explosion
B—1-Sec Benioff
HS—1/2-Sec Hall-Sears HS-10
W—1-Sec Willmore Mark I
ET—1-Sec Electrotech EV-17
V—Vertical
T—Transverse
L—Longitudinal

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
TAPE LOOP NO. 5							
1	EQ	1/26/59	Hollister, Calif.	Mt. Hamilton, Calif.	95	VW	2.7
2	N-EX	12/10/61	Hope, N. Mex.	Carlsbad, N. Mex.	100	VW	4.0
3	EQ	6/30/62	Winslow, Ariz.		160	VHS	0.9
4	N-EX		Castle Cliffs, Utah	NTS, Nev.	187	VW	4.2
5	EQ	8/24/59	Shepherd, Mont.	Hebgen Lake, Mont.	240	VW	2.9
6	N-EX		Quarter Master View Pt., Ariz.	NTS, Nev.	235	VW	2.6
7	EQ	12/13/61	Magdalena, N. Nex.		315	VW	2.2
8	N-EX		Pica, Ariz.	NTS, Nev.	350	VW	3.1
9	EQ	1/26/59	Hollister, Calif.	Owens Valley, Calif.	432	VW	4.0
10	N-EX		Hollister, Calif.	NTS, Nev.	450	VW	3.1
11	EQ	7/24/60	St. George, Utah	Cloudcroft, N. Mex.	638	VW	4.5
12	N-EX		Rifle, Colo.	NTS, Nev.	786	VW	4.1
13	EQ	5/19/62	U of M Well, Mich.	Acapulco, Mexico	3000	VHS	
14	N-EX		Fiborn Quarry, Mich.	NTS, Nev.	3000	VHS	3.35
TAPE LOOP NO. 6							
1	EQ	7/30/62	Neapolis, Crete		402	VHS	5.1
2	U-EX	7/1/61	Coopers Mill, Maine	Offshore Maine	150	VW	
3	EQ	7/28/62	Neapolis, Crete		128	VHS	2.7
4	U-EX	8/26/61	DeBell's Ranch, Calif.	Off San Clemente Isle, Calif.	123	VW	4.1
5	EQ	4/23/62	Concepción, Chile		310	VHS	3.65
6	C-EX	7/1/58	Star Lake, New York	St. Lawrence Seaway	100	VW	3.35
7	EQ	1/26/59	Hollister, Calif.	Mt. Hamilton, Calif.	118	VW	3.0

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
8	EX	8/3/61	Scope Lake, Alberta	Suffield, Alberta	100	VHS	2.2
9	EQ	5/14/62	Rincon, Puerto Rico		90	VHS	1.35
10	Q-EX	8/6/59	Hendricks Quarry, Mich.	Rogers City Quarry, Mich.	156	VW	0.2
11	EQ	4/23/62	Concepción, Chile		115	VHS	2.65
12	Q-EX	8/4/59	Hendricks Quarry, Mich.	Rogers City Quarry, Mich.	156	VW	0.8
13	EQ	8/25/59	McLeod, Mont.	Hebgen Lake, Mont.	110	VW	2.3
14	Q-EX	7/12/61	Hendricks Quarry, Mich.	Rogers City Quarry, Mich.	156	VB	5.6
TAPE LOOP NO. 7							
1	EQ	8/25/59	McLeod, Mont.	Hebgen Lake, Mont.	110	VW	2.4
2	Q-EX	6/29/62	Fiborn Quarry, Mich.	Cedarville Quarry, Mich.	70.2	VHS	1.9
3	EQ	8/25/59	McLeod, Mont.	Hebgen Lake, Mont.	110	VW	2.0
4	U-EX	8/20/62	Barnett Chapel, Ky.	Off Cape Girardeau, Mo.	100	VHS	0.8
5	EQ	4/22/62	Concepción, Chile		103	VHS	3.4
6	U-EX	8/20/62	Barnett Chapel, Ky.	Off Cape Girardeau, Mo.	100	VHS	0.8
7	EQ	7/29/62	Neapolis, Crete		167	VHS	3.2
8	U-EX	7/1/61	Coopers Mill, Maine	Offshore Maine	146	VW	2.4
9	EQ	4/23/62	Concepción, Chile		310	VHS	3.65
10	U-EX	7/1/61	Coopers Mill, Maine	Offshore Maine	165	VW	2.4
11	EQ	8/13/61	Mt. Laguna, Calif.		123	VW	2.4
12	U-EX	8/30/61	DeBell's Ranch, Calif.	Off San Clemente Isle, Calif.	123	VW	2.8
13	EQ	8/9/61	Chief Peak, Calif.		92	VW	1.4

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
14	U-EX	9/2/61	DeBell's Ranch, Calif.	Off San Clemente Isle, Calif.	123	VW	1.6
TAPE LOOP NO. 8							
1	EQ	8/13/61	Mt. Laguna, Calif.		90	VW	1.4
2	N-EX		Radio Crystal, Nev.	NTS, Nev.	150	VW	2.8
3	EQ	8/18/61	Mt. Laguna, Calif.		94	VW	0.8
4	U-EX	8/20/62	Barnett Chapel, Ky.	Off Cape Girardeau, Mo.	97.4	VW	1.2
5	EQ	4/20/61	Hollister, Calif.		85	VW	
6	EQ	1/28/59	Hollister, Calif.	Mt. Hamilton, Calif.	95	VW	2.7
7	EQ	4/16/61	Hollister, Calif.		120	VW	
8	EQ	8/23/59	Red Lodge, Mont.	Hebgen Lake, Mont.	150	VW	3.6
9	EQ	4/23/61	Panoche, Calif.		150	VW	1.7
10	EQ	8/23/59	Red Lodge, Mont.	Hebgen Lake, Mont.	155	VW	2.2
11	EQ	7/28/60	St. George, Utah		87	VW	
12	N-EX		Climax Claims, Ariz.	NTS, Nev.	212	VHS	3.8
13	EQ	3/1/62	Castle Cliffs, Utah		78	VW	0.5
14	EQ	7/31/62	Neapolis, Crete		142	VHS	2.8
TAPE LOOP NO. 9							
1	EQ	4/24/62	Concepción, Chile		48	VHS	2.55
2	Q-EX	8/17/62	Townsend, Mont.	Trident Quarry, Mont.	80	VHS	2.7
3	EQ	4/16/61	Hollister, Calif.		45	VW	0.5
4	Q-EX	6/29/62	Fiborn Quarry, Mich.	Cedarville, Mich.	70.2	VHS	2.1
5	EQ	7/28/62	Neapolis, Crete		76	VHS	2.7
6	Q-EX	8/11/61	Nett Lake, Minn.	Morton Quarry, Minn.	70	VW	0.3

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
7	EQ	4/24/62	Concepción, Chile		50	VHS	2.8
8	N-EX		Corn Creek, Nev.	NTS, Nev.	75	VHS	0.4
9	EQ	7/7/62	Climax Claims, Ariz.		60	VHS	0.4
10	Q-EX	8/13/62	Townsend, Mont.	Wolf Creek, Mont.	60	VHS	0.5
11	EQ	6/9/61	Mauna Loa, Hawaii		32	VW	2.0
12	Q-EX	7/6/62	Fiborn Quarry, Mich.	Cedarville, Mich.	70.2	VHS	1.2
13	EQ	5/12/62	Rincon, Puerto Rico		45	VHS	1.15
14	Q-EX	8/10/61	Nett Lake, Minn.	Pierce Mine, Minn.	81.6	VW	0.3
TAPE LOOP NO. 10							
1	EQ	4/16/61	Hollister, Calif.		200	VW	2.1
2	Q-EX	7/13/62	Fiborn Quarry, Mich.	Humboldt Quarry Mich.	213.9	VHS	2.7
3	EQ	8/22/59	Edgar, Mont.	Hebgen Lake, Mont.	200	VW	1.9
4	U-EX	8/3/62	Clayton, N. C.	Offshore North Carolina	215.4	VW	2.3
5	EQ	8/24/59	Shepherd, Mont.	Hebgen Lake, Mont.	210	VW	2.3
6	U-EX	8/18/62	Waverly, Tenn.	Off Cape Girardeau, Mo.	200	VHS	1.8
7	EQ	5/30/62	Coconut Pt., Amer. Samoa		200	VW	4.5
8	N-EX		Climax Claims, Ariz.	NTS, Nev.	217	VW	3.4
9	EQ	5/31/62	Coconut Pt., Amer. Samoa		200	VHS	3.6
10	N-EX		Castle Cliffs, Utah	NTS, Nev.	190	VW	4.2
11	EQ	8/24/59	Shepherd, Mont.	Hebgen Lake, Mont.	225	VW	2.3
12	N-EX		Climax Claims, Ariz.	NTS, Nev.	226	VW	4.8

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
13	EQ	8/24/59	Shepherd, Mont.	Hebgen Lake, Mont.	210	VW	2.5
14	U-EX	8/18/62	Waverly, Tenn.	Off Cape Girardeau, Mo.	200	VHS	1.8
TAPE LOOP NO. 11							
1	EQ	5/31/62	Coconut Pt., Amer. Samoa		315	VHS	4.3
2	U-EX	7/5/61	Hope, Maine	Offshore Maine	284.4	VW	2.4
3	EQ	5/29/62	Coconut Pt., Amer. Samoa		390	VHS	4.2
4	U-EX	7/2/61	Coopers Mill, Maine	Offshore Maine	300	VW	2.4
5	EQ	4/23/62	Concepción, Chile		310	VHS	3.65
6	N-EX		Pica, Ariz.	NTS, Nev.	322	VW	3.1
7	EQ	4/24/62	Concepción, Chile		280	VHS	3.1
8	N-EX		Willow Springs, Ariz.	NTS, Nev.	271	VW	2.6
9	EQ	1/28/59	Hollister, Calif.		432	VW	4.0
10	N-EX		Winslow, Ariz.	NTS, Nev.	554	VHS	3.1
11	EQ	7/24/60	St. George, Utah		700	VW	3.9
12	U-EX	7/1/61	Coopers Mill, Maine	Offshore Maine	277.7	VW	2.2
13	EQ	7/24/60	Kingman, Ariz.		650	VW	3.2
14	N-EX		Rifle, Colo.	NTS, Nev.	780	VW	4.8
TAPE LOOP NO. 12							
1	EQ	8/18/61	Mt. Laguna, Calif.		93	VW	1.3
2	Q-EX	7/6/62	Fiborn Quarry, Mich.	Rogers City Quarry, Mich.	140	VW	4.0
3	EQ	4/23/61	Hollister, Calif.		150	VW	1.2
4	Q-EX	9/20/62	Fiborn Quarry, Mich.	Humboldt Quarry, Mich.	200	VB	1.3
5	EQ	7/28/60	St. George, Utah		87	VW	1.3
6	Q-EX	7/6/62	Fiborn Quarry, Mich.	Rogers City Quarry, Mich.	140	VHS	4.0

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
7	EQ	5/28/62	Coconut Pt., Amer. Samoa		140	VHS	3.8
8	N-EX	12/10/61	Hope, New Mexico	Carlsband, New Mexico	100	VW	4.0
9	EQ	7/31/62	Neapolis, Crete		116	VHS	2.7
10	Q-EX	8/19/60	Hendricks Quarry, Mich.	Rogers City Quarry, Mich.	156	VW	1.7
11	EQ	4/23/62	Concepción, Chile		127	VHS	2.25
12	Q-EX	7/11/62	Fiborn Quarry, Mich.	Rogers City Quarry, Mich.	141	VHS	2.1
13	EQ	8/16/61	Mt. Laguna, Calif.		144	VW	1.4
14	N-EX		Radio Crystal, Nev.	NTS, Nev.	189	VW	2.6
TAPE LOOP NO. 13							
1	N-EX		Radio Crystal, Nev.	NTS, Nev.	189	VW	2.6
2	N-EX		Radio Crystal, Nev.	NTS, Nev.	189	TW	2.6
3	N-EX		Castle Cliffs, Utah	NTS, Nev.	217	VW	3.0
4	N-EX		Castle Cliffs, Utah	NTS, Nev.	217	TW	3.0
5	Q-EX	2/23/62	Ramona, Calif.	Eagle Mt. Mine, Calif.	150	VW	
6	Q-EX	2/23/62	Ramona, Calif.	Eagle Mt. Mine, Calif.	150	LW	
7	EQ	8/16/61	Mt. Laguna, Calif.		144	VW	1.4
8	EQ	8/16/61	Mt. Laguna, Calif.		144	N-SW	1.4
9	EQ	12/13/61	Luera Ranch, N. Mex.		315	VB	2.2
10	EQ	12/13/61	Luera Ranch, N. Mex.		315	TB	2.2
11	EQ	12/13/61	Luera Ranch, N. Mex.		315	VW	2.2
12	EQ	12/13/61	Luera Ranch, N. Mex.		315	LB	2.2

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
13	N-EX		Quarter Master View Pt., Ariz.	NTS, Nev.	235	VB	2.6
14	N-EX		Quarter Master View Pt., Ariz.	NTS, Nev.	235	TB	2.6
TAPE LOOP NO. 14							
1	EQ	7/28/60	Kingman, Ariz.		276	VB	2.2
2	C-EX	9/27/60	Kanab, Utah	NTS, Nev.	315	VW	2.2
3	C-EX	10/13/60	Kanab, Utah	NTS, Nev.	287	VW	3.5
4	EQ	9/27/60	Kanab, Utah		275	VW	
5	EQ	4/16/61	Hollister, Calif.		315	VW	
6	N-EX		Climax Claims, Ariz.	NTS, Nev.	220	VHS	1.8
7	EQ	7/27/60	Kingman, Ariz.		220	VB	1.4
8	N-EX		Climax Claims, Ariz.	NTS, Nev.	225	VHS	3.8
9	EQ	12/13/61	Luera Ranch, N. Mex.		315	VW	2.2
10	N-EX		Climax Claims, Ariz.	NTS, Nev.	225	VHS	3.4
11	EQ	7/28/60	St. George, Utah		320	VW	
12	N-EX		Climax Claims, Ariz.	NTS, Nev.	225	VHS	3.7
13	EQ	1/28/59	Hollister, Calif.		432	VW	4.0
14	N-EX		Winslow, Ariz.	NTS, Nev.	562	VW	4.8
TAPE LOOP NO. 15							
1	EQ	7/2/63	Shepherd, Mont.	Denver, Colo.	720	VET	4.2
2	U-EX	7/18/63	Copper Harbor, Mich.	Lake Superior	255	VHS	2.6
3	EQ	7/7/63	Shepherd, Mont.	Central Utah	750	VHS	4.9
4	Q-EX	7/12/61	Hendricks Quarry, Mich.	Babbit Quarry, Minn.	521	VB	3.7
5	EQ	8/31/63	Chicken Springs, Oregon	Monterey Cty., Calif.	700	HHS	4.3
6	U-EX	7/25/63	Eagle Lake, Minn.	Lake Superior	400	VHS	1.6
7	EQ	7/7/63	Shepherd, Mont.	Off Coast of N. Calif.	1400	VHS	4.7

Channel No.	Event	Date	Recording Location	Source Location	Distance (km)	Seis-mometer	Magnitude (M)
8	N-EX		Magdalena, N. Mex.	NTS, Nev.	840	VB	2.8
9	EQ	8/30/62	Marysville, Calif.	Cache Creek, Utah	850	SP-Z Lo	5.5
10	N-EX		Bonneville, Wyo.	NTS, Nev.	1000	VHS	3.6
11	EQ	9/16/63	100 Mile House, B. C.	Kern County, Calif.	1760	SP-Z Hi	5.0
12	N-EX		Idaho Springs, Colo.	NTS, Nev.	1100	VHS	4.8
13	EQ	9/5/62	Marysville, Calif.	Cache Creek, Utah	850	SP-Z Hi	4.6
14	N-EX		Truth or Conse-quences, N. Mex.	NTS, Nev.	940	VW	2.8
TAPE LOOP NO. 16							
1	EQ	7/8/63	Shepherd, Mont.	Mexico-Guatemala	3625	VHS	4.5
2	N-EX		Beverly, Ohio	NTS, Nev.	3000	VHS	5.5
3	EQ	7/8/63	Shepherd, Mont.	Kodiak Is., Alaska	4500	VHS	4.6
4	N-EX		Fiborn Quarry, Mich.	NTS, Nev.	3000	VHS	5.5
5	EQ	7/8/63	Shepherd, Mont.	Colombia	5550	VHS	4.0
6	N-EX		U of M Well, Ann Arbor, Mich.	NTS, Nev.	3000	VHS	5.5
7	EQ	7/9/63	Shepherd, Mont.	Costa Rica, Panama	4750	VHS	5.1
8	N-EX		Fiborn Quarry, Mich.	NTS, Nev.	3000	VHS	4.7
9	EQ	8/29/63	Berry Creek, Nev.	Off Coast of Peru	6400	VHS	6.5
10	N-EX		Washington, Georgia	NTS, Nev.	3000	VHS	5.5
11	EQ	7/1/63	Shepherd, Mont.	Kurile Islands	7000	VHS	4.5
12	N-EX		Shepherd, Mont.	Fallon, Nev.	1100	VHS	4.9
13	EQ	9/1/63	Chicken Springs, Oregon	Nicaragua	4500	VHS	4.4
14	N-EX		Idaho Springs, Colo.	NTS, Nev.	1100	VHS	3.4

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